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Evaluation of a Seat Attenuation System for the Orion Crew Module

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March 2008

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Summary

The function of the crew seat attenuation system for the Orion Crew Module (CM) is to provide the crew with a low injury-risk landing environment under a range of crew configurations and landing conditions. The current design for the seat attenuation system provides the crew an environment with a low risk of injury, based on the Brinkley criteria for most of the landing conditions considered. Furthermore, the stroking of the seat attenuation system is within limits, and the clearance between the seat support platform and vehicle is not exceeded. For the limited number of landing conditions where a low injury risk is exceeded, the risk is never beyond a moderate level. The results presented in this study are based on a CM structural model that is rigid except for the pallet struts, which attenuate landing loads and reduce the accelerations transferred to the astronauts. The CM simulations include a soft soil landing. Several different crew configurations are evaluated in this study. It is expected that situations where the risk is "above low" can be eliminated in future design iterations.

Introduction

The function of the crew seat attenuation system for the Orion Crew Module (CM) is to provide the crew with a low injury-risk landing environment under a range of crew configurations and landing conditions. During CM landing, the Orion crew members are restrained in seats, which are mounted on a frame that is connected to the CM through the seat attenuation system. During landing, the attenuation system is designed to minimize the landing accelerations incurred by the crew members. The attenuation system, which accommodate landing loads in all three directions of travel (vertical, horizontal, and lateral), absorbs landing impact energy through stroking mechanisms built into the seat attenuation. The purpose of this paper is to evaluate the structural dynamic performance of the attenuation system in terms of acceleration levels, strut stroke, and injury risks to the crew members.

Ideally, a detailed structural model of the CM and an accurate model of the landing medium would be used to simulate each of the land landing scenarios. The detailed model of the vehicle would include the elastic and nonlinear behavior of all the structural components including the contribution of damping and energy-absorbing components such as crushable materials on the bottom vehicle outer shell, as well as shock absorbers used to mount the pallet by the astronaut seats. Additionally, the model would include any landing attenuation system such as retrorockets and parachutes. This model would be capable of accurately predicting transient accelerations throughout the vehicle in addition to where the astronauts are seated, and would be able to predict stress levels in vehicle components throughout the vehicle structure.

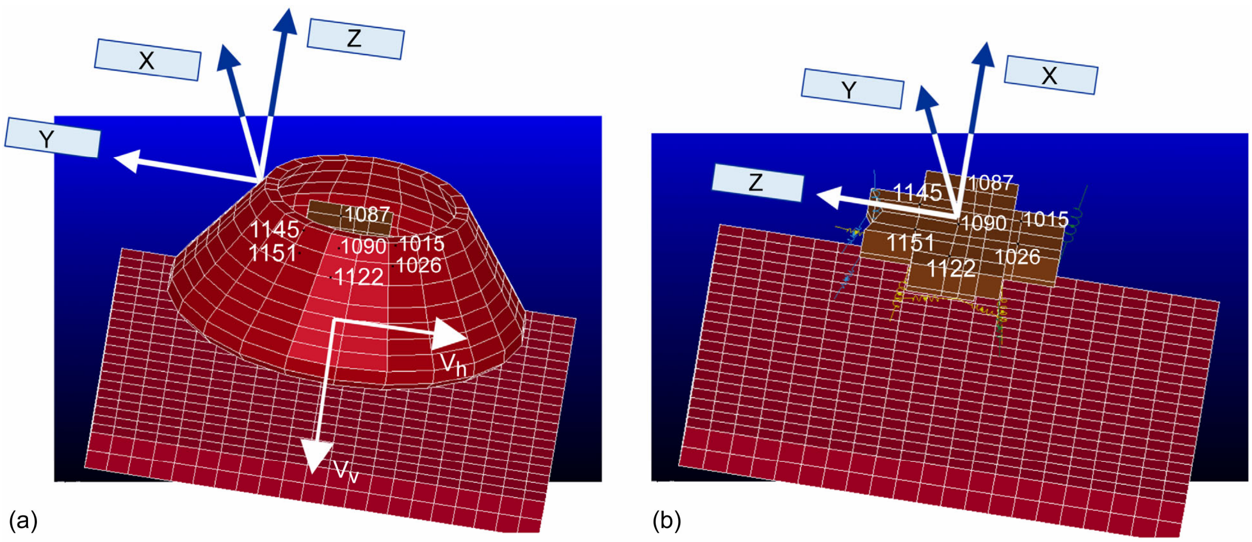


Figure 1.—The 604 seat attenuation model. (a) Global coordinate system. (b) Brinkley local coordinate system (pressure vessel not shown).

The model of the landing medium would fully characterize the actual landing soil behavior including the actual deformation of the soil and the soil's contribution to energy absorption from the incoming vehicle, both in the vertical and horizontal directions. However, for the present study, a simplified structural model of the vehicle and landing surface are employed (fig. 1). A simplified model is used since a higher fidelity model is not available at the time of this study. The simplified model consists of an astronaut pallet supported by energy-absorbing struts attached to a rigid structural model of the vehicle. The landing medium is modeled as a simple elastic-plastic material with energy-absorbing behavior. Further details of the model are provided later in this report.

Crew Exploration Vehicle Model

The finite element program, LS–DYNA is used to perform the analysis of CM land landings. This commercially available program is selected because of its ability to simulate the complex transient dynamic behavior of the CM impacting a landing surface. The CM model consists of a collection of structural parts. The main portion of the vehicle, which consists of the pressure vessel, associated structure, and internal components, is modeled as a rigid part having inertia properties equivalent to the Lockheed Martin (LM) 604 Crew Module design (table I). Since this part is modeled as rigid, it acts as a rigid mass and exhibits no structural deformation, and no structural loadings are computed for the part.

TABLE I.—SEAT ATTENUATION MODEL PART LIST

Part no.	Description
1	CM vessel (rigid inertia)
2	Strut set 1 (elastoplastic discrete springs) K_1=30 000 lb/in., K_2=300 lb/in., F_y=3000 lb
3	Strut set 2 (elastoplastic discrete springs) K_1=30 000 lb/in., K_2=300 lb/in., F_y =2500 lb
4	Strut set 3 (elastoplastic discrete springs) K_1=30 000 lb/in., K_2=200 lb/in., F_y =2000 lb
5	Astronaut pallet (rigid inertia)
6	Elastoplastic soil
7	Strut sets 1, 2, 3 (viscous discrete dampers)

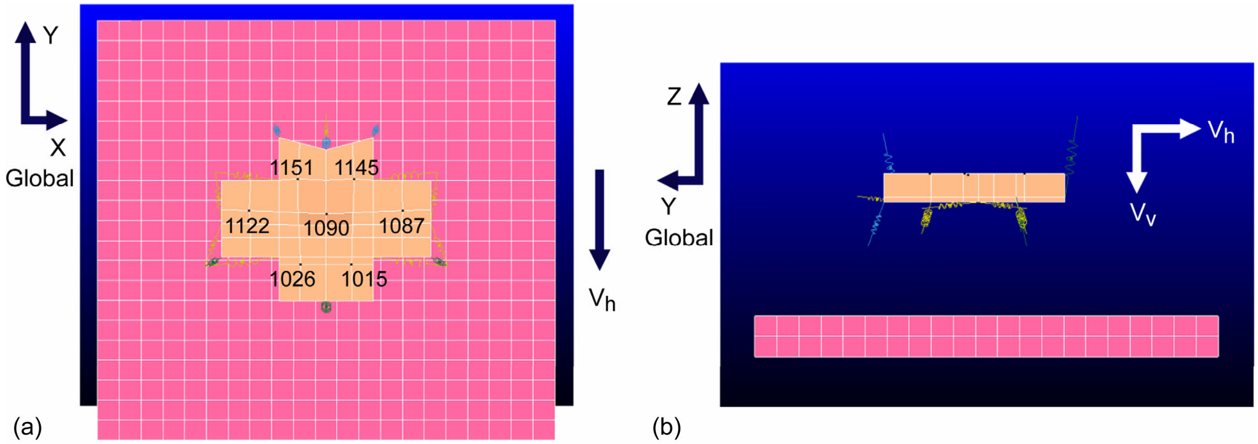


Figure 2.—The 604 seat platform. (a) Seat attenuation model, top view. (b) Seat attenuation model, side view.

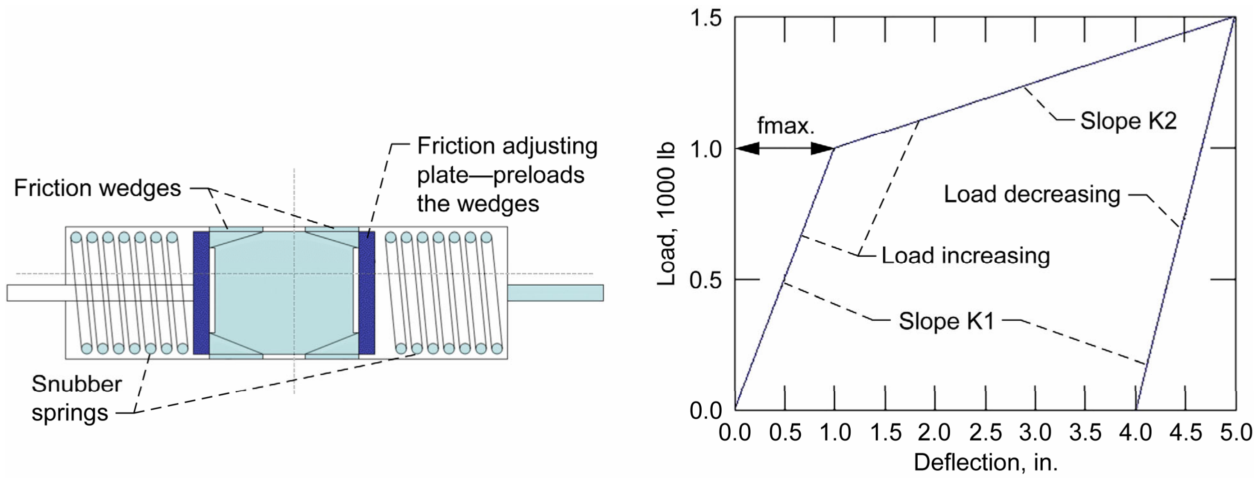


Figure 3.—Friction strut characteristics.

Inside of the CM pressure vessel is the astronaut pallet (fig. 2). The pallet supports the astronaut seats and is supported by 15 energy-absorbing landing struts. A portion of the vehicle inertia properties are allocated to the pallet (modeled as a rigid part) to account for the astronaut and seat weights. While the pressure vessel and pallet are modeled as structurally rigid and non-energy-absorbing, the pallet struts are modeled as energy-absorbing since they provide the primary source of landing load attenuation.

The seat attenuation struts are modeled as elastic-plastic friction devices (fig. 3). Each strut behaves like an elastic linear spring (K_1) up until a yield force (F_y) is reached, at which point the strut stiffness is reduced to a relatively low value (K_2), as shown in the plastic region of the curve. On rebound (load decreasing), the strut follows the slope of original (K_1) elastic load-deflection curve. The energy that each strut absorbs is equal to the area under the load-deflection curve. The struts are grouped in three sets with each set having the properties defined in table I. The schematic in figure 3 depicting the strut design is notional, and many different strut designs may be implemented with this described behavior. Alternately, other strut designs with different behaviors could be employed in the future.

Note that the acceleration predictions resulting from the present model are dependent on the assumption of a rigid pressure vessel and pallet model and the assumptions used for the pallet strut designs. Since the struts are designed for a specific acceleration limit and modeled with a constant force behavior, they are in fact designed to perform optimally for a single design point and will perform less than optimally for off-nominal design conditions. A tradeoff in the strut design is made since they can be designed to accommodate a worse-case condition or nominal conditions, but not both. It should also be

Soil type	ρ, lb $s^2/in.^4$	E, psi	σ_Y, psi	E_h, psi
Soft	2.06	580.	9.99	116.
Medium	2.06	5800.	99.9	1160.
Hard	2.06	19,000.	323.0	3812.
Rigid	2.25	$2.5\ 10{\times}^6$	3000.	—

Representative soil models

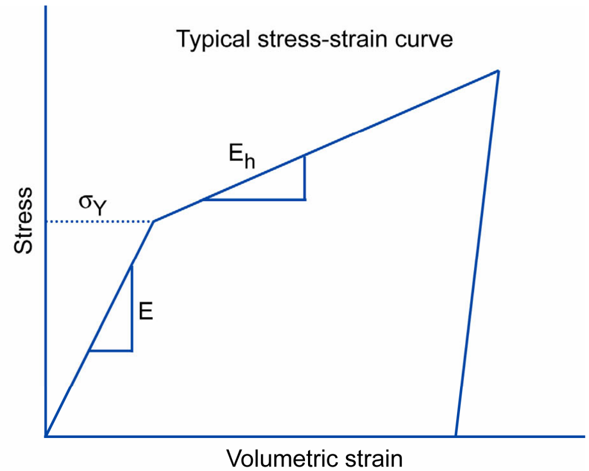


Figure 4.—LS–DYNA soil material model.

noted that the actual pallet support system may employ another type of attenuation system that performs differently from the present design. For example, an active attenuation system could be used, in which case a feedback loop would enable the struts to perform optimally for a broader range of landing conditions.

In reality, the vehicle landing surface will be some type of soil that will deform on impact and absorb energy. Defining a model for the landing surface is a challenge since the landing site is currently undefined. Furthermore, even for a known site, the condition of the soil can be variable ranging from a hard surface produced, for example, by a dry summer to a soft soil produced by spring precipitation. For the purpose of the present study, the landing surface is assumed to be a soft soil (fig. 4). The soft-soil model has the effect of reducing the resulting vehicle accelerations compensating for rigidity of the modeled vehicle structure.

Tables II and III show soil models affect the vehicle accelerations. As expected, the vehicle accelerations are higher for the stiffer soil properties. The medium soil model produces significantly higher vehicle accelerations than the soft soil model. At this point, it is a judgment call as to which soil model to use. However, as previously mentioned, it is reasonable to use the softer soil since the vehicle is modeled as mostly rigid. In the future as the vehicle structure is better defined and more refined structural models can be implemented, an alternate soil model may be more appropriate.

TABLE II.—COMPARISON FOR THREE SOIL MODELS
[Heavyweight six-crew (1376 lb[a])—Vehicle CG reported
V_v=13 fps, V_h= 58 fps]

Horizontal velocity, fps	Soft soil, friction = 0.1		Soft soil, friction = 0.6		Medium soil, friction = 0.6	
	Max. X[b], Z[c] acceleration, g	Rollover	Max. X, Z acceleration, g	Rollover	Max. X, Z acceleration, g	Rollover
10	8.21, 5.67	No	8.33, 9.32	No	22.24, 21.26	No
40	10.11, 5.23	No	8.90, 14.33	No	21.72, 26.6	No
58	13.47, 7.45	No	9.84, 1576	No	27.41, 34.20	No

[a]Changed to 1461 lb for remainder of study.
[b]X = eyes-in/out.
[c]Z = spine.

TABLE III.—604 ROLLOVER STUDY, HEAVYWEIGHT SIX-CREW 15° CONTACT (TOE-DOWN), SOFT SOIL

Contact friction	Vertical velocity, fps	Horizontal velocity, fps	Rollover
0.60	13	58	No
1.00	13	58	Yes
0.60	26	58	No
1.00	26	58	Yes

A major concern during landing is vehicle rollover. For certain combinations of vehicle orientation and landing velocity, vehicle rollover will occur. In addition to the soil conditions and the vehicle center-of-gravity orientation, two of the primary parameters that effect rollover are vehicle pitch angle and horizontal landing velocity. Figure 5 depicts the relationship between the vehicle pitch angle, horizontal velocity, and vehicle rollover. In general the vehicle is more prone to rollover with higher horizontal landing velocities. However, when the vehicle lands in a toe-in (toe-in or toe-down is where the front of the vehicle contacts the ground before the rear) orientation in the range of 15° to 25°, the vehicle is especially stable even for high horizontal landing velocities. This result is important and should strongly influence the parachute attachment design so that this range of contact angle is attained during land landing.

The results in table III confirm the trends of figure 5 for the present vehicle. The present vehicle, which is designed with a hang angle of 15°, does not roll over even when it lands with a horizontal velocity of 58 fps. In fact, the vehicle did not roll over until the contact friction was increased to 1.00. This friction value is extreme considering that a soft soil model was used and there already was a significant amount of plowing even without any friction. A friction coefficient of 0.60 will be used for the remainder of the results presented in this paper.

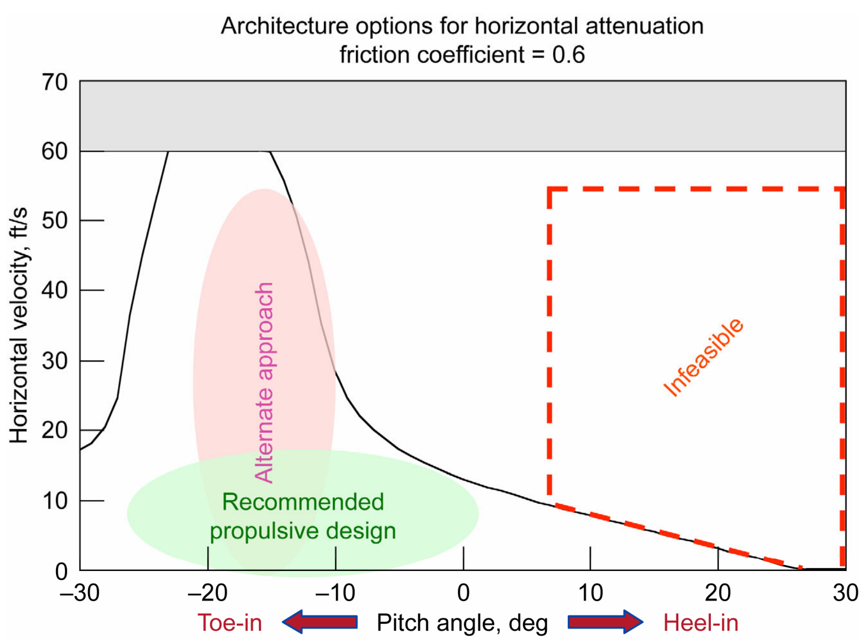


Figure 5.—LS–DYNA simulation rollover results for retro-rocket landings. (Courtesy of Karen Lyle and Mercedes Reaves, NASA Langley Research Center).

Figure 6 shows the landing conditions that were used for the present study. The landing conditions are defined in terms of horizontal and vertical landing velocities and vehicle orientation. These conditions are determined by variables such as parachute conditions, wind speeds, and crew combinations. The primary focus of the present study was to determine the effect of different crew configurations so most of the landing conditions were held constant and four different crew configurations were evaluated; a six-person heavyweight crew, a four-person crew, a two-person lightweight crew, and a single crew.

For each set of landing conditions, a transient dynamic simulation is performed, and resulting acceleration profiles are extracted and used to determine astronaut injury risk levels using a human body injury model.

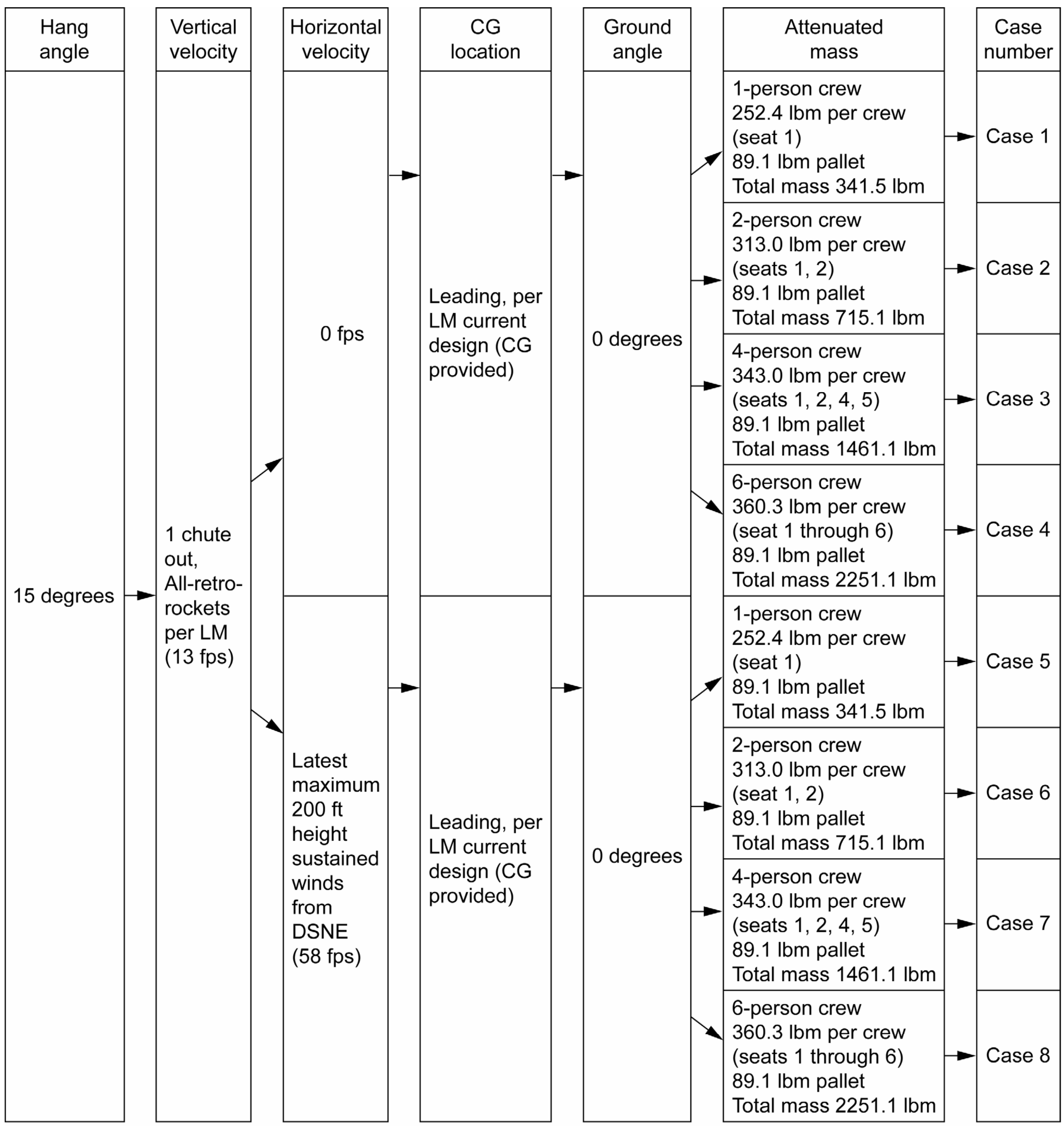


Figure 6.—Landing initial conditions.

Figures 7 and 8, and table IV show the crew orientation and vehicle inertia properties for the various crew configurations. The inertia properties of the vehicle are distributed between the pressure vessel and the crew pallet. The pressure vessel properties remain constant while the pallet inertia properties change depending on the crew configuration. For all of the crew configurations, the pallet center-of-gravity is symmetric about the z-axis, except for the single-crew configuration which has a z-axis offset. The center-of-gravity location for the two-, four-, and six-crew configurations are symmetric about the y-axis while the single-crew configuration is offset from the y-axis due to the odd number of crew members.

TABLE IV.—VEHICLE INERTIAL PROPERTIES[a]

Components	Inertial properties						
	Mass, CG, in.	Ixx	Iyy	Izz	Ixy	Iyz	Ixz
Vehicle total, [b] 13 045 lb	33.798 (0, –4.4, 1050)	87,000 psi/ 386	80,000 psi/ 386	118,000 psi/ 386	–3000 psi/ 386	–2500 psi/ 386	–4000 psi/ 386
Pressure vessel, 10 795 lb (13 046 to 2250.9)	27.97 (0, –3.78, 1047)	71,124.	54,346.	76,470.	–2504.	–2500.	–4000.
Heavyweight six-crew, 2250.9 lb	5.831 (0, 7.37, 1063.7)	15,876.	25,654.	41,530.	–496.	0.	0.
Four-crew, 1461.1 lb	3.785 (0, 7.37, 1063.7)	10,159.	3300.	13,456.	–314.	0.	0.
Lightweight two-crew, 714.7 lb	1.852 (0, 30.7, 1063.7)	125.	889.	889.	0.	0.	0.
Lightweight one-crew, 401.9 lb	1.04 (–12.2, 25.4, 1063.7)	336.	293.4	607.2	–74.66	0.	0.

[a]Vehicle properties about vehicle CG. Pallet properties about pallet CG.
[b]From CEV–T–045004, August 2006.

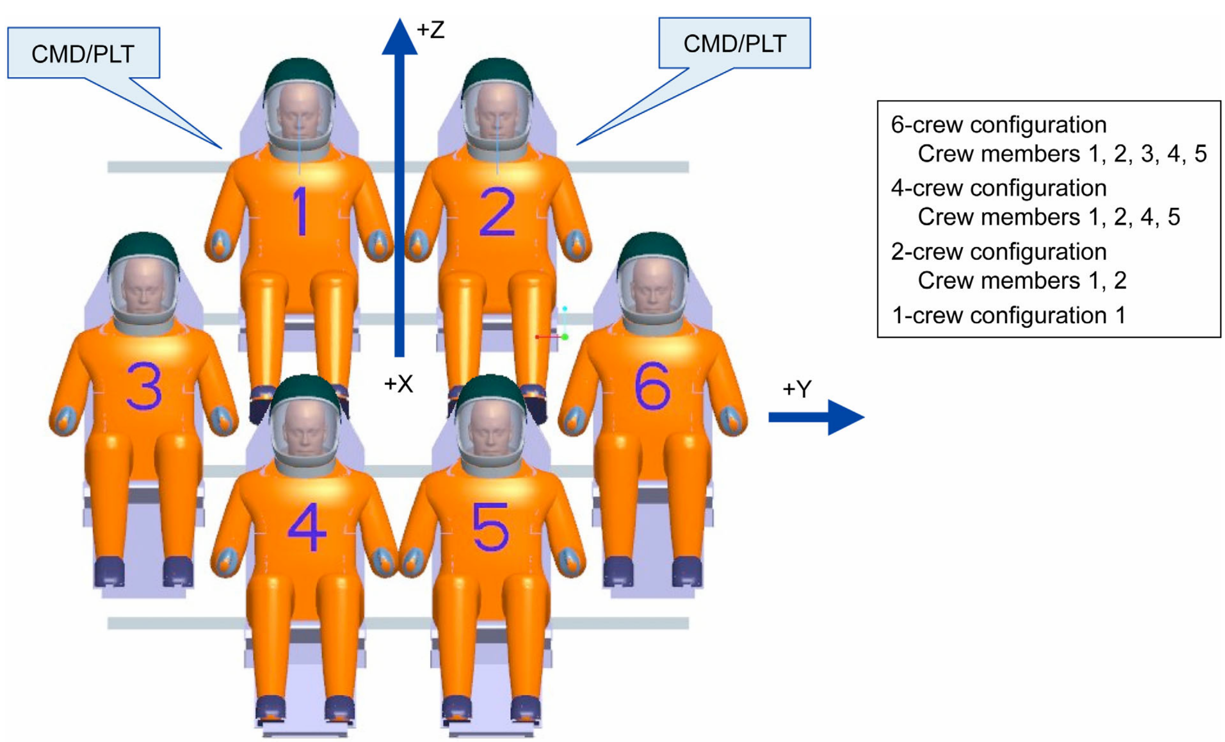


Figure 7.—Crew configurations.

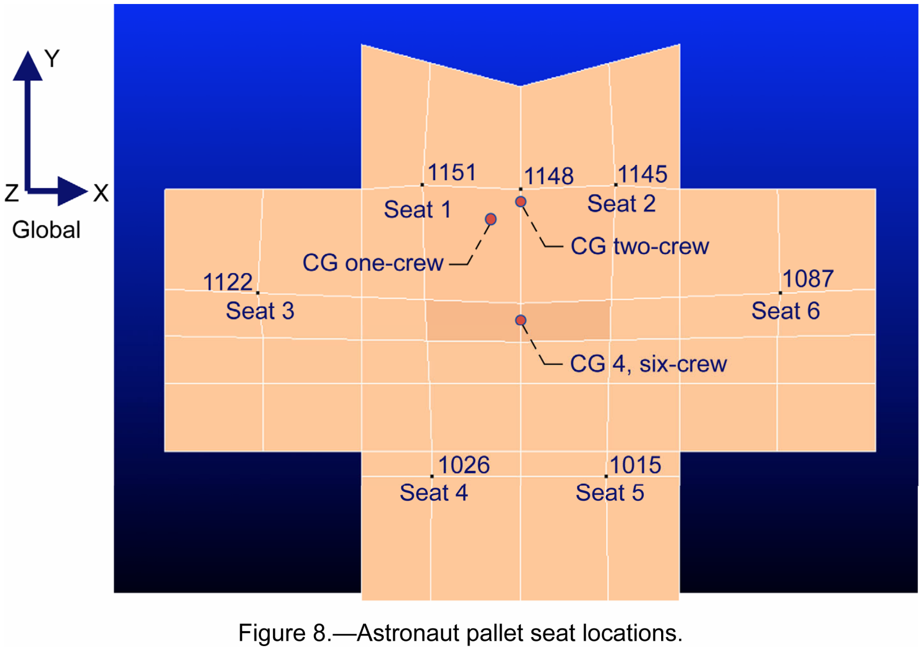


Figure 8.—Astronaut pallet seat locations.

Simulation Results

LS–DYNA was used to perform transient simulations and obtain time history transient responses for the landing conditions previously described. The results are reported in a body fixed coordinate system that is fixed in the vehicle and rotates as the vehicle rotates (fig. 1). The axes of this body fixed system correspond to the directions that are used to assess injury risk levels to the astronauts. The body fixed x-axis, y-axis, and z-axis correspond to the eyes-in/out, sideways, and spine directions of the astronauts in the vehicle. The use of these axes allows for the acceleration time histories to be directly input into the Brinkley model used to assess astronaut injury risk. The criteria used to access astronaut risk are shown in table V. The NASA Human Systems Integration Requirements (HSIR) for the Orion vehicle differ slightly from the Brinkley criteria but it should be noted that regardless of which criteria are used the computed accelerations are derived from the Brinkley human response model.

TABLE V.—ASTRONAUT INJURY RISK CRITERIA ALLOWABLE ACCELERATION, g

Injury criteria		Direction					
		Chest-in/out		Sideways		Spinal	
		A>0 (Chest-out)	A<0 (Chest-in)	A>0	A<0	A>0 (Spine-up)	A<0 (Spine-down)
Very low risk	Brinkley[a]	N/A	N/A	N/A	N/A	N/A	N/A
	HSIR	31.0	22.4	11.8	11.8	13.1	11.0
Low risk	Brinkley[a]	35.0	28.0	14/15	14/15	15.2	9/13.4
	HSIR	35.0	28.0	14.0	14.0	15.2	13.4
Moderate risk	Brinkley[a]	40.0	35.0	17/20	17/20	18.0	12/16.5
	HSIR	N/A	N/A	N/A	N/A	N/A	N/A
High risk	Brinkley[a]	46.0	46.0	22/30	22/30	22.8	15/20.4
	HSIR	N/A	N/A	N/A	N/A	N/A	N/A

[a]From “Development of Acceleration Exposure Limits for Advanced Escape Systems” by Brinkley, et al., updated Brinkley.

Figures 9 to 11 contain a summary of the simulation results for a vertical and horizontal landing velocity of 13 and 0 fps, respectively. The results are for the lightweight two-crew, four-crew, and heavyweight six-crew configurations. The maximum strut stroke and force within each set of struts are reported in each of the figures. The dynamic response index (DRI) computed from the Brinkley model is computed for each seat location and the maximum value is reported in the figures. For all crew configurations the computed DRIs are in the HSIR very low risk category in both the eyes-in/out and the spinal directions. Furthermore, for this landing condition, the struts either do not reach their yield force or just pass the point of yielding, and the strut strokes are relatively small. As expected, the largest strut force and stroke occurs for the six-crew configuration. A sideways acceleration is not reported since the vehicle and landing is symmetric about this axis and there is negligible response in this direction.

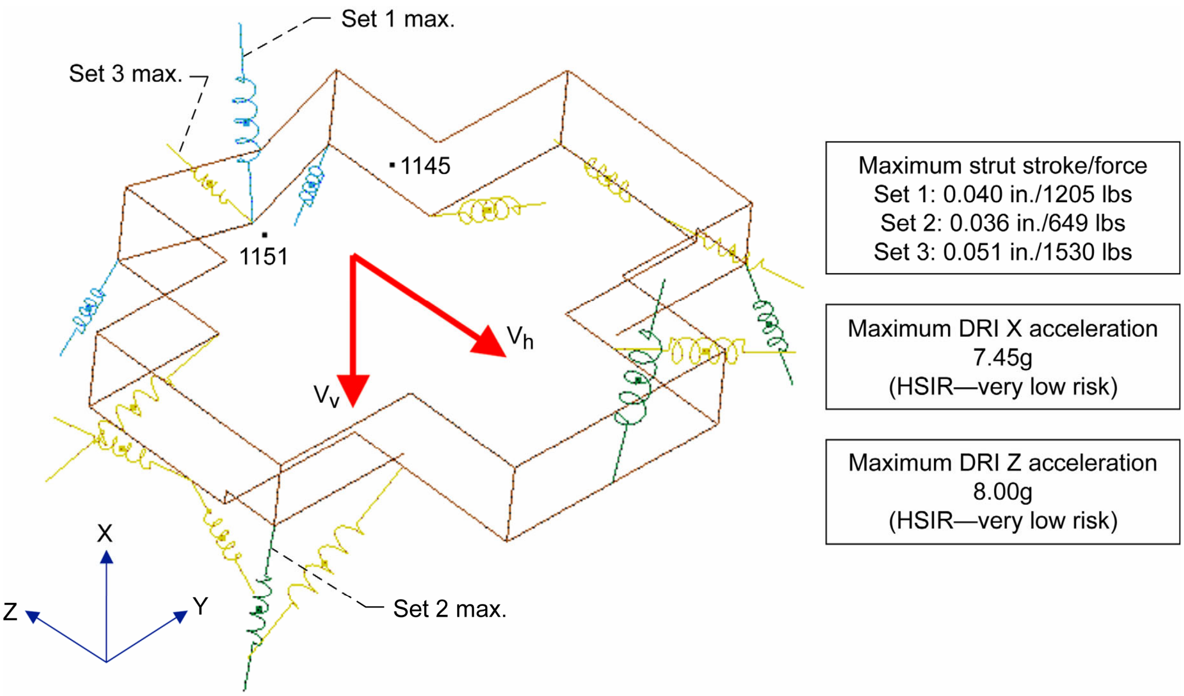


Figure 9.—Light 2-crew, V_v = 13 fps, V_h = 0 fps.

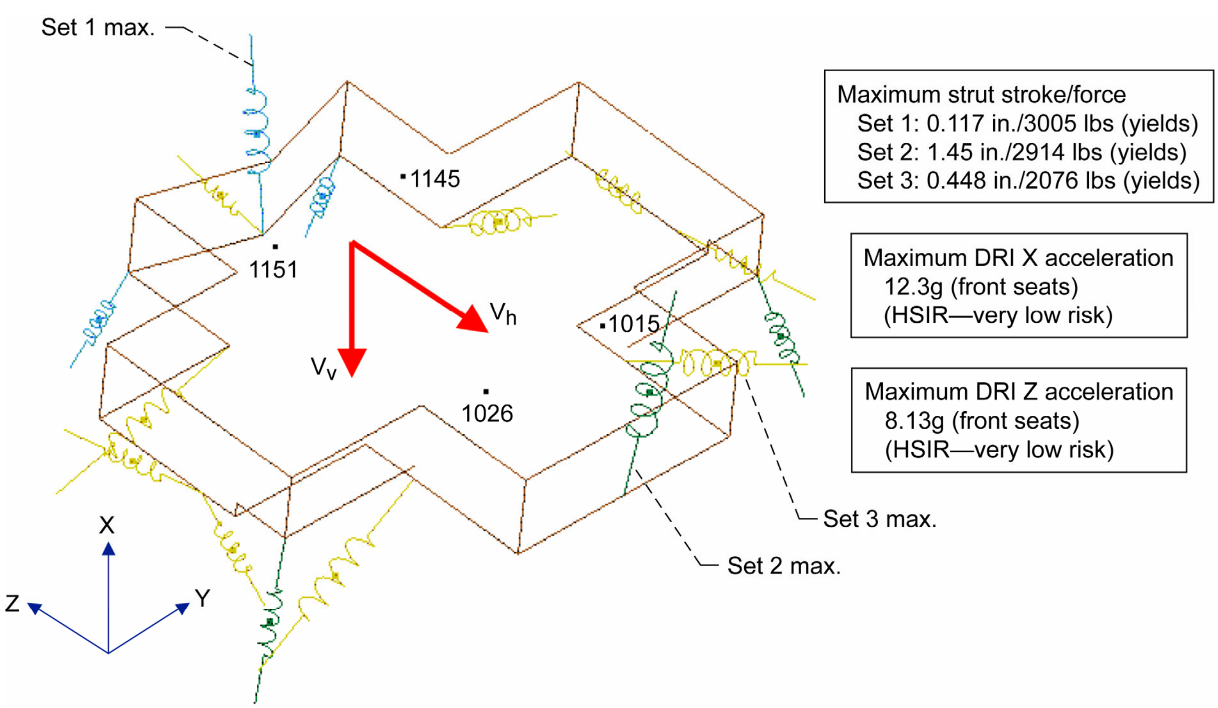


Figure 10.—Light 4-crew, V_v = 13 fps, V_h = 0 fps.

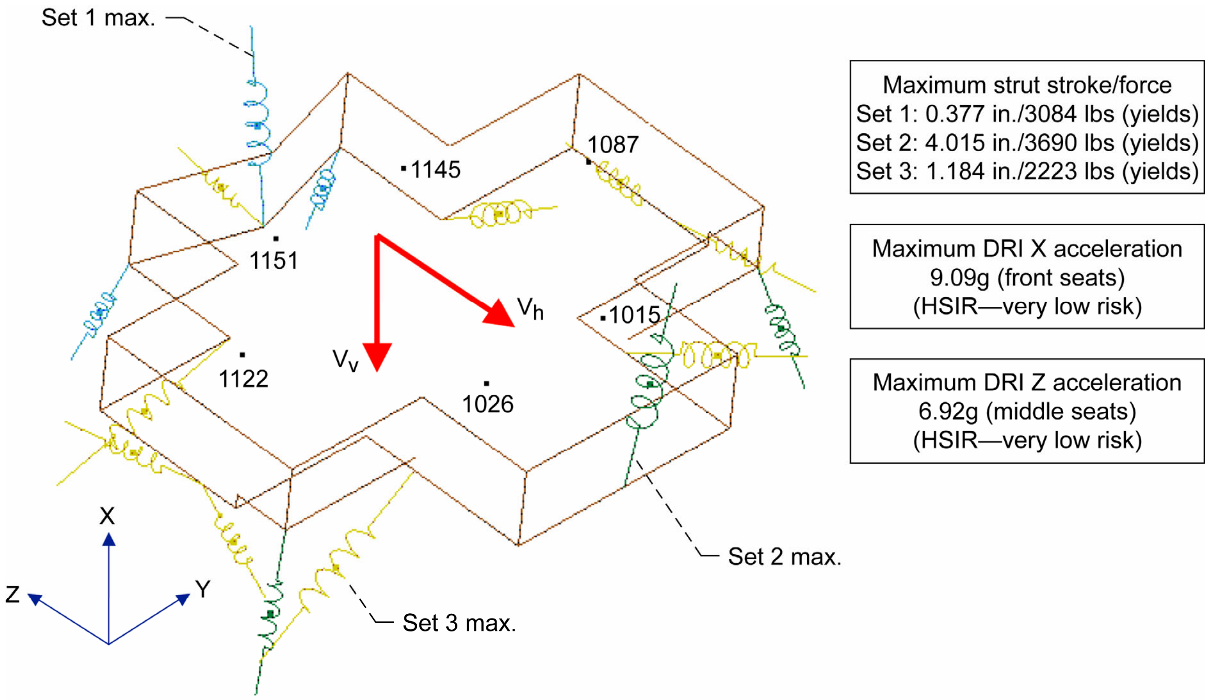


Figure 11.—Heavy 6-crew, V_v = 13 fps, V_h = 0 fps.

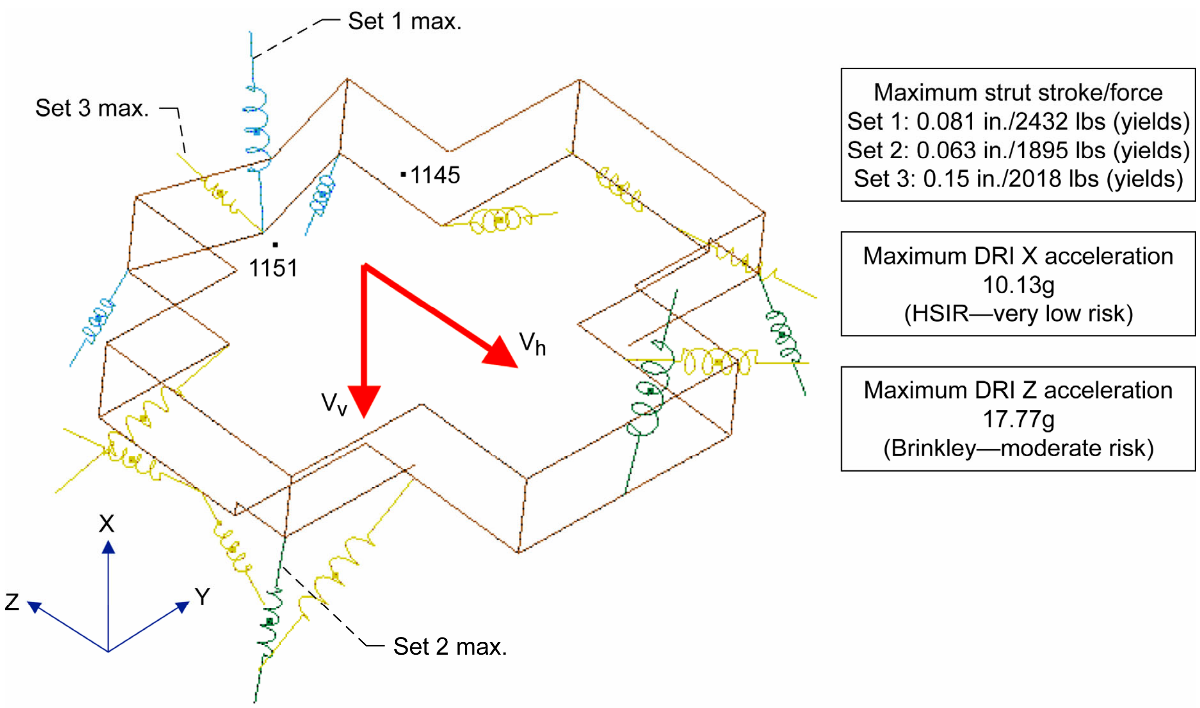


Figure 12.—Light 2-crew, V_v = 13 fps, V_h = 58 fps.

Figures 12 to 14 contain a summary of the simulation results for a vertical and horizontal landing velocity of 13 and 58 fps, respectively. For all crew configurations, the strut force, stroke, and DRI accelerations are greater than the previous case where the horizontal velocity is 0 fps. Even though the accelerations are larger for this landing condition, the injury risk level remains very low except for the two-crew and four-crew spinal risks, which is moderate and low risk, respectively. It is important to note that while the astronauts are seated in an optimal position to minimize injury risk for a vertical only landing, they are seated in an undesirable position to accommodate horizontal landing loads since the horizontal direction coincides with the spinal direction and the spinal direction is less tolerant to acceleration than the chest-in/out direction.

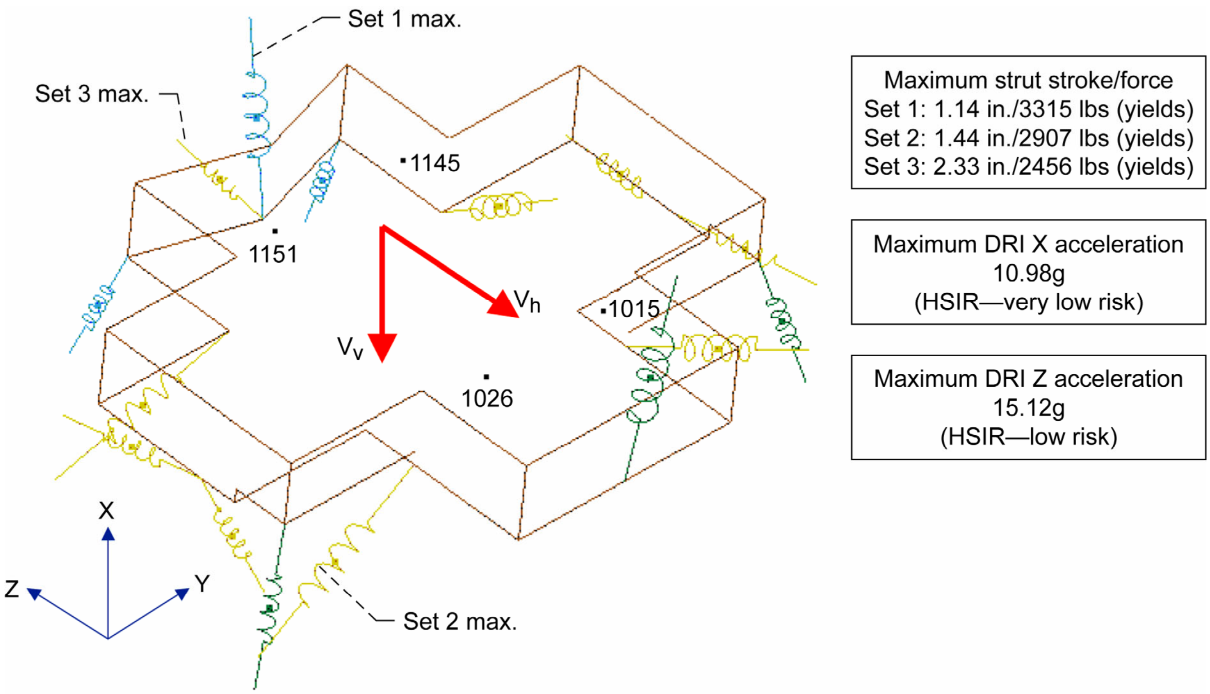


Figure 13.—Light 4-crew, V_v = 13 fps, V_h = 58 fps.

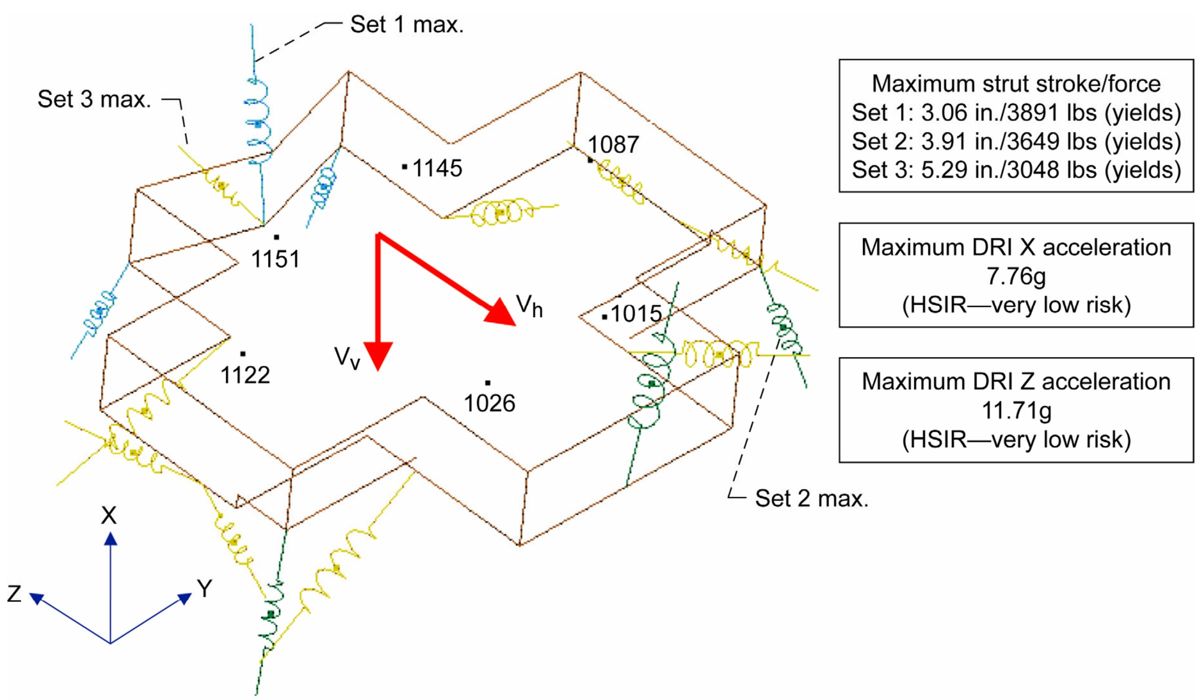


Figure 14.—Heavy 6-crew, V_v = 13 fps, V_h = 58 fps.

Figures 15 and 16 show a summary of the maximum DRIs in the eyes-in/out and spinal directions for both the 0 and 58 fps horizontal landing velocities. The center-of-gravity location for the six-crew configuration was moved forward and backward 12 in. to assess the effect of CG location while the rest of the crew configuration results are reported for their actual CG locations. For the spinal direction the CG location had negligible effect while for the eyes-in/out direction relocating the CG did have an effect on the resulting DRIs although the risk levels remained in the very low range.

It was expected that as the number and weight of the crew increased acceleration would decrease and strut stroke would increase. That is, the struts would act "soft" for a heavyweight crew and therefore minimize accelerations and maximize strut stroke. Conversely, the strut system would feel "stiff" for a lightweight crew, which would see higher accelerations and less strut stroke. The results in these figures do not follow this expected trend. Instead, for some cases the four-crew configuration actually incurs higher DRI acceleration than the two-person crew.

The results shown in figure 17 are used to explain why the lightest crew does not incur the largest injury risk. By comparing the peak transient accelerations designated by the blue curves in figure 17 for each of the crew configurations, it is seen that the maximum acceleration actually follows the expected trend of a higher acceleration for a lighter crew. However, by examining the frequency of the transient response, it is noticeable that the acceleration profile associated with the lighter crew is higher in frequency than for the heavier crews. The higher frequency is logical since the lighter crew has the effect of raising the resonant vibration frequency of the seat platform. Since the frequency content is higher, the DRI values generated by the Brinkley model are lower than expected since the Brinkley model is more out of tune with the acceleration profile for the lighter crew than for the other crew configurations.

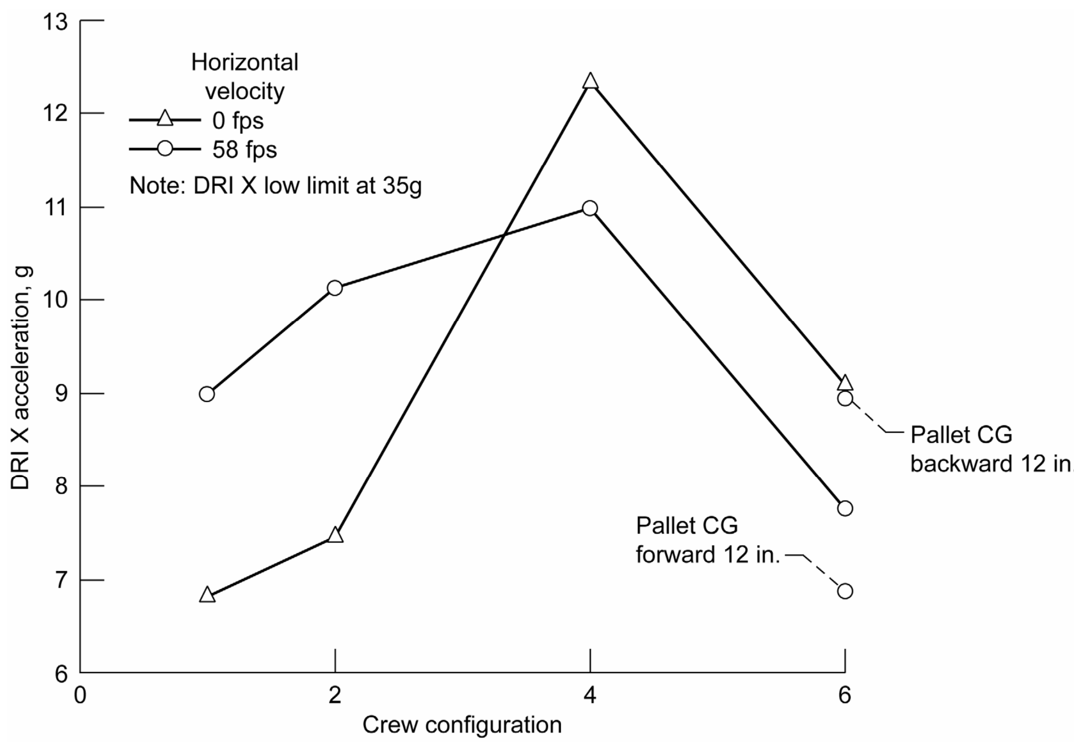


Figure 15.—Maximum DRI X (eye in/out) acceleration V_V = 13 fps.

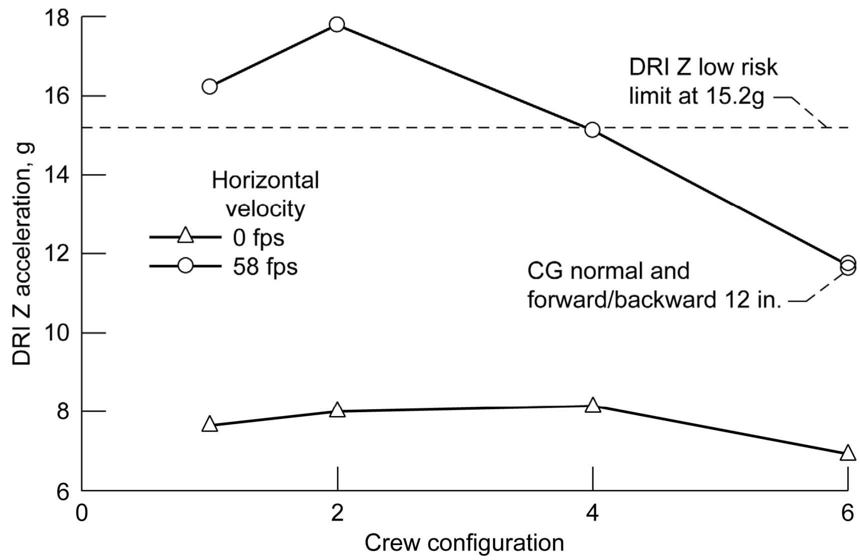


Figure 16.—Maximum DRI Z (spinal) acceleration V_v = 13 fps.

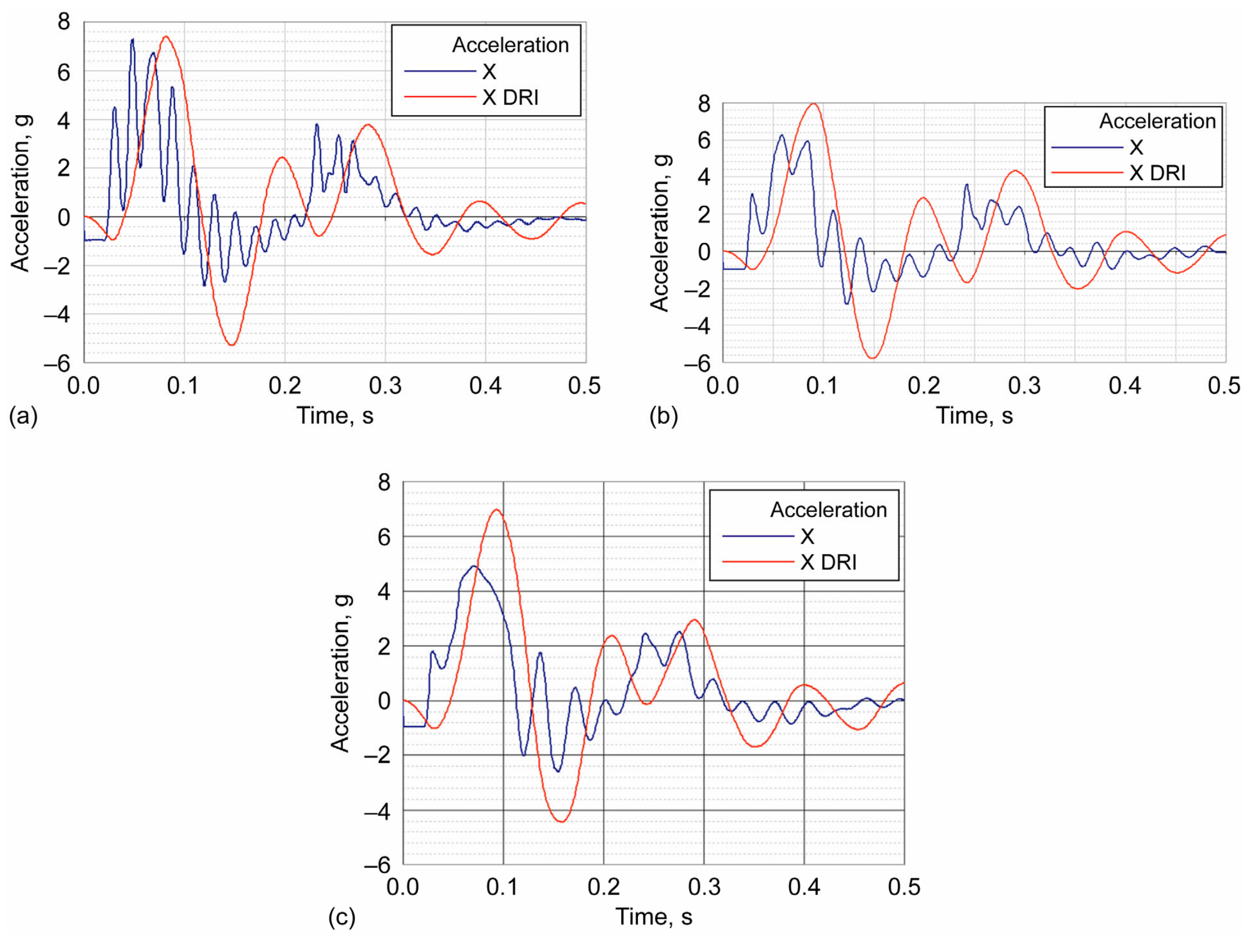


Figure 17.—Seat 1 acceleration and resulting DRI, V_v = 13 fps, V_h = 0 fps. (a) Two-crew configuration. (b) Four-crew configuration. (c) Six-crew configuration.

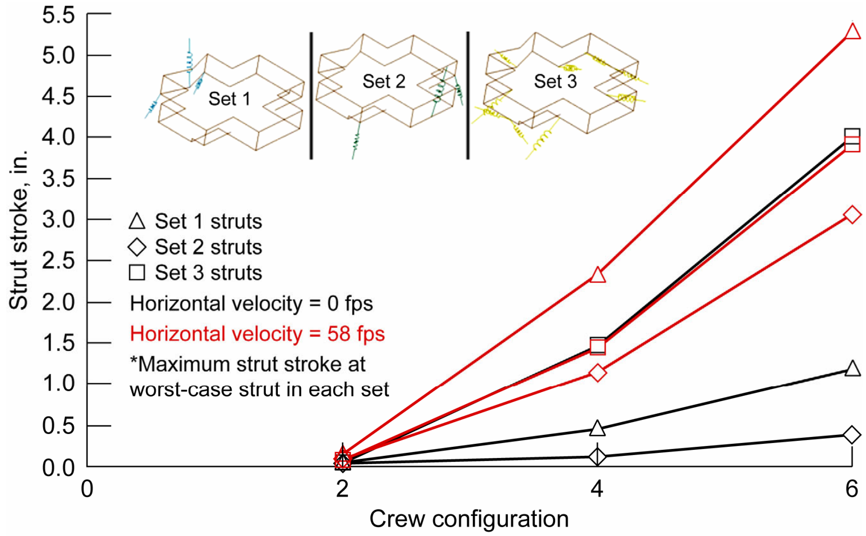


Figure 18.—Maximum strut stroke.*

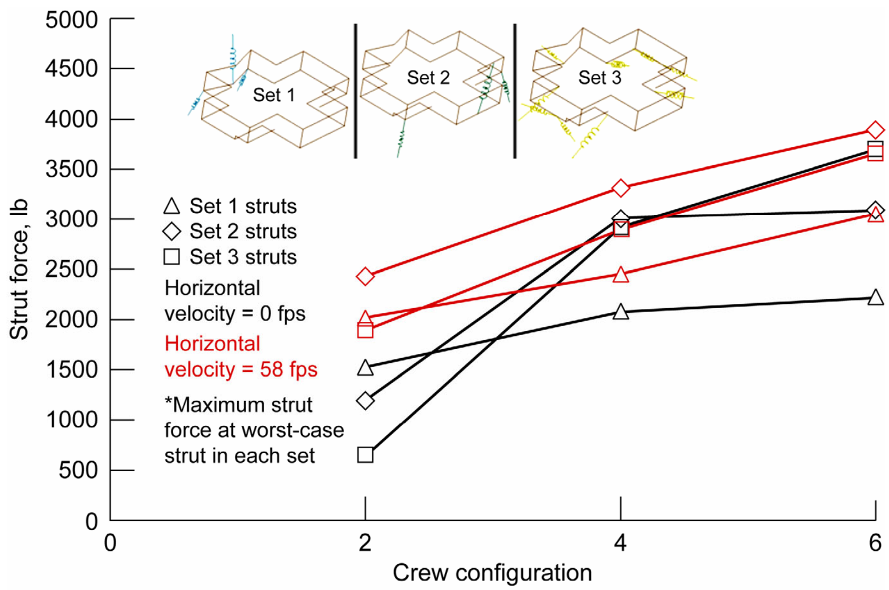


Figure 19.—Maximum strut force.*

Figures 18 and 19 provide the maximum strut stroke and force for each of the crew configurations and landing conditions. The six-crew configuration incurs the largest strut stroke and force, while the smallest crew incurs the least stroke and force. In general, the strut forces barely exceed their yield force, thus absorbing a minimal amount of energy. The strut stroke is relatively small, thus minimizing any difficulties associate with clearance between the seat support frame and the rest of the vehicle.

In addition to the Brinkley injury measures in each of the individual axes, the Brinkley model provides a “Beta” value that provides an overall measure of injury risk (fig. 20). The Beta value is equal to the square root of the sum of the squares of the DRIs in each direction divided by the Brinkley allowable DRIs for each direction. The Beta value is computed for each of the low, medium, and high levels of injury risk. A Beta value below 1.0 indicates that the risk is acceptable and conversely a Beta value over 1.0 indicates a potential of risk for the specified risk level. For this study, three conditions generated a Beta value above 1.0; the two-crew and four-crew with a horizontal landing velocity of 58 fps. The HSIR has a Beta requirement similar to the Brinkley Beta requirement. The difference is that the HSIR uses the acceleration limits shown in table V and the vehicle is limited to “very low risk” during nominal landing conditions and “low risk” during off-nominal conditions like chute-out landings.

In addition to strut force, stroke, and injury risk, it is also important to monitor the clearance between the seat support structure and the adjacent vehicle to ensure that the support structure does not collide with the adjacent structure. The present model is only an approximation to the real geometry so the clearances predicted by this model are an approximation to the actual clearances. However, the present model is capable of providing at least an initial estimate of the clearance between the seat support structure and vehicle. The clearance was predicted using the present model by identifying edges of the pallet that are closest to the outer shell of the vehicle. The transient displacement response at these locations was then monitored, and the relative distance between these points were plotted (figs. 21 and 22). Both the front and side clearance were plotted and as shown in the plots, the available clearance was never exceeded.

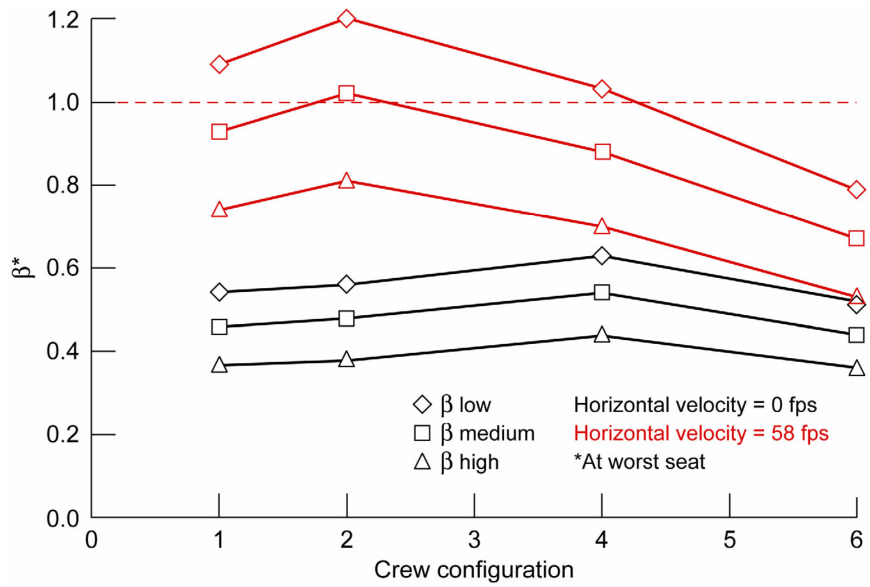
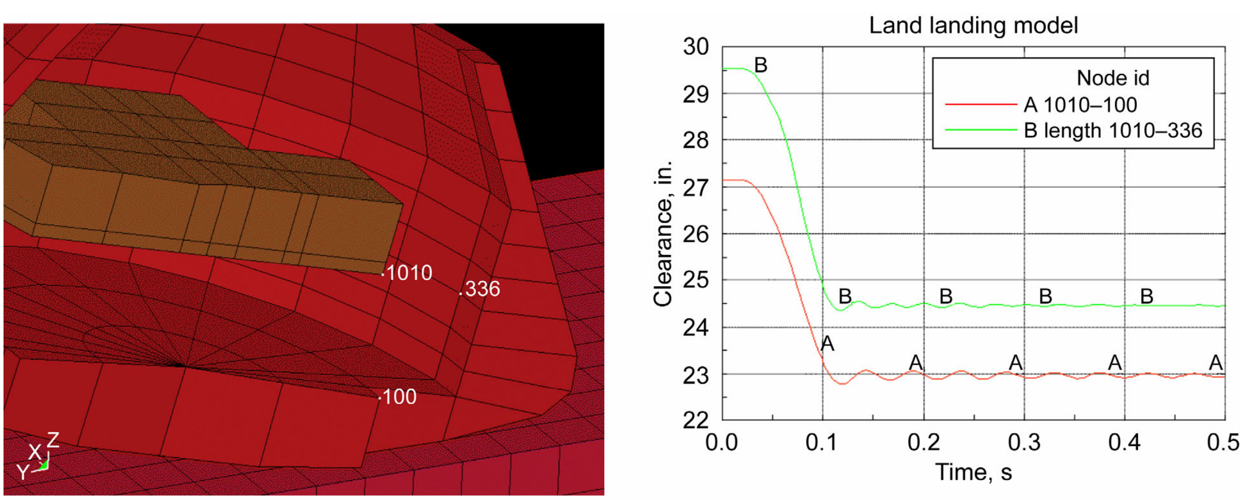
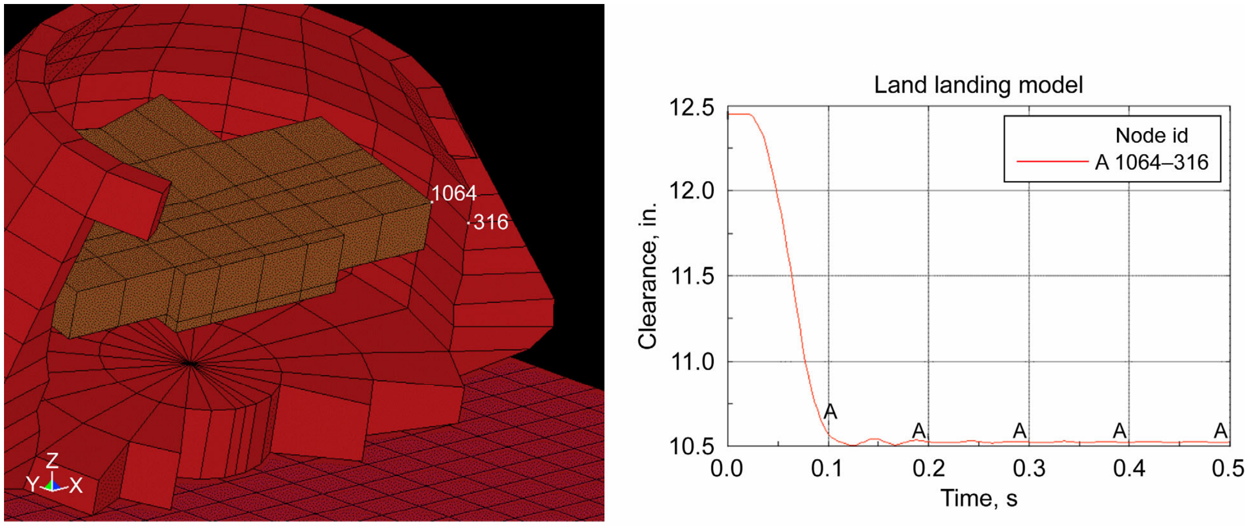


Figure 20.—Summary of Brinkley β values.*



- Node 1010–edge of pallet
- Node 336–inside wall of pressure vessel
- Node 100–bottom of pressure vessel

Figure 21.—Front clearance 6-crew configuration, V_v = 13 fps, V_h = 58 fps.



• Node 1064–side of pallet
• Node 316–inside wall of pressure vessel

Figure 22.—Side clearance 6-crew configuration, V_v = 13 fps, V_h = 58 fps.

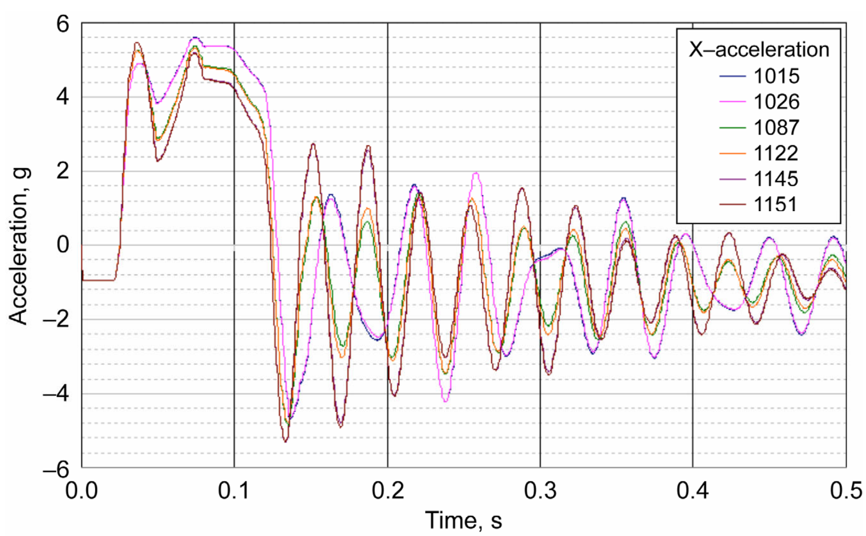


Figure 23.—X (eyes in/out) acceleration versus seat position heavy 6-crew configuration, V_v = 13 fps, V_h = 58 fps.

Figures 23 and 24 show the eyes-in/out and spinal acceleration profiles for each of seat locations for the heavyweight six-crew configuration. The results presented thus far have used the worse-case or maximum accelerations, so it is useful to compare the accelerations at each seat location to better understand the variability of the acceleration with seat location. For the most part, there is very little variability among the different seat locations, and it is therefore probably not necessary to always examine acceleration profiles at every seat and instead to merely use the acceleration profiles at the seat support structure CG. This is particularly true for the two-, four-, and six-crew configurations since they are symmetric about the direction of landing, but may not be valid for the single-crew configuration which has no axis of symmetry.

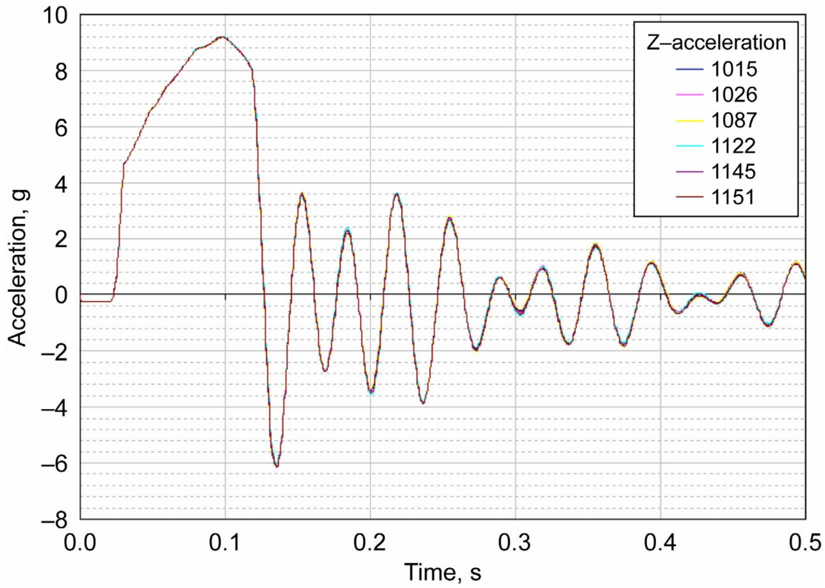


Figure 24.—Z (spinal) acceleration versus seat position heavy 6-crew configuration, V_v = 13 fps, V_h = 58 fps.

Concluding Remarks

The current preliminary design for the seat attenuation system provides the crew with a low risk of injury based on the Brinkley criteria for most of the landing conditions considered. Furthermore, the stroking of the seat attenuation system is within limits and the clearance between the seat support platform and vehicle is not exceeded. For the few landing conditions where a low injury risk is exceeded, the risk is never beyond a moderate level. It is expected that the few situations where the risk is above low can be eliminated in future design iterations. It should be noted that although the landing conditions considered capture a broad range of conditions, other landing conditions that are more critical may occur as the program develops.

The results presented in this study are based on a CM structural model that is rigid except for the pallet struts, which attenuate landing loads and reduce the accelerations transferred to the astronauts. This model does not account for structural flexibility or damage. These effects, which are expected to reduce the seat accelerations, were offset in the present study by employing a relatively soft soil model.

More detailed design of the pallet struts and alternate strut mechanisms beyond a simple elastic-plastic design should be considered. It is expected that future work will include investigation of alternate strut designs such as actively controlled systems and adjustment capability for heavier and lighter crew members and configurations.

The expected trend that a lightweight crew would see larger accelerations and a heavyweight crew would see large displacements was discounted by the fact the injury response is frequency dependent and the crew weight affects the frequency content of the acceleration profiles. This phenomenon provides a design challenge that may be used as a design advantage for attenuating injury risk. Future work should included assessing higher fidelity models of the CM that include damage, alternate strut designs, and possibly a broader range of landing conditions.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The function of the crew seat attenuation system for the Orion Crew Module (CM) is to provide the crew with a low injury-risk landing environment under a range of crew configurations and landing conditions. The current design for the seat attenuation system provides the crew with a low risk of injury environment based on the Brinkley criteria for most of the landing conditions considered. Furthermore, the stroking of the seat attenuation system is within limits, and the clearance between the seat support platform and vehicle is not exceeded. For the limited number of landing conditions where a low injury risk is exceeded, the risk is never beyond a moderate level. The results presented in this study are based on a CM structural model that is rigid except for the pallet struts, which attenuate landing loads and reduce the accelerations transferred to the astronauts. The CM simulations include a soft soil landing. Several different crew configurations are evaluated in this study. It is expected that situations where the risk is above low can be eliminated in future design iterations.

15. SUBJECT TERMS
Spacecraft design; Landing; Astronauts; Risk

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